Polarization Engineered Normally-Off GaN/InAlN/AlN/GaN HEMT

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There is an interest in using a recessed gate technology for a development of normally-off InAlN/GaN-based high electron mobility transistors (HEMTs) [1-3]. Plasma etching was suggested to recess the gate until 1-2 nm thick barrier layer remains. However, such a short gate-to-channel distance may severely affect the Schottky barrier (SB) gate leakage current I_G and the device off-state breakdown voltage V_{BR} [1, 2]. Gate insulation by an oxide layer has been successfully demonstrated to improve V_{BR} [3]. In the present study, we propose a normally-off HEMT with a 2 nm thick InAlN/AlN barrier but with an undoped 2 nm GaN cap. The negative polarization charge at the GaN/InAlN junction is effective to deplete the channel below the gate and simultaneously to enhance an effective SB and to reduce I_G, similarly as demonstrated earlier for AlGaN/GaN [4]. On the other hand, after removing the GaN cap at access regions, electrons populate the extrinsic channel. For the etching step, Ir/Au gate is used as a mask to keep the gate region intact. Consequently, high V_{BR} and low I_G are achieved without additional gate insulation. Principle of the concept is verified also by a two-dimensional numerical device simulation.

2 µm gate-length HEMTs with a source-to-drain distance 8 µm are prepared on MOCVD-grown $GaN/In_{0.17}Al_{0.83}N/AlN/GaN$. GaN is removed at access regions by selective CCl_2F_2-based dry etching. Finally, HEMTs are passivated with 10 nm Al_2O_3 and annealed at 700°C. A TLM test pattern indicates that the channel sheet resistance drops from ~15 kΩ/□ to ~2.5 kΩ/□ after removing the GaN cap, and to ~1.5 kΩ/□ after the passivation/annealing. We observed some shift of V_T after the annealing step towards the negative values, which is opposite to what was reported elsewhere [2], still V_T remains positive in most cases. Completed HEMTs show 150-200 mA/mm drain current at $V_{GS} = 2$ V and $V_T \sim 0.3$ V. By modeling the InAlN surface potential is extracted to be 1.6 eV after the GaN etching and 1.5 eV after the passivation. I_G is $\sim 10^{-7}$ A/mm during three-terminal subthreshold measurements ($V_{GS} < V_T$) at V_{DS} up-to 200 V (maximum scale of the Keithley 4200-SCS). Thus a hard V_{BR} is above 200 V which a record for SB normally-off InAlN/GaN HEMTs.

[1] J. Kuzmik et al., *IEEE TED* **57** 2144 (2010), [2] R. Wang et al., *IEEE EDL* **32** 309 (2011), [3] D. Morgan et al., *APEX* **4** 114101 (2011), [4] E.T. Yu et al., *APL* **73** 1880 (1998).

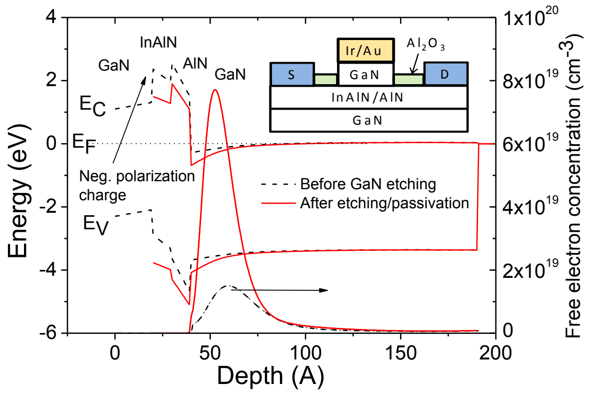

Fig.1. Calculated energy band and electron concentration profiles at (GaN)/InAlN/AlN/GaN HEMT access regions before and after etching the GaN cap. Value of a surface potential is 1.1 eV for GaN and 1.5 eV for InAlN. Inset shows sketch of the completed HEMT.

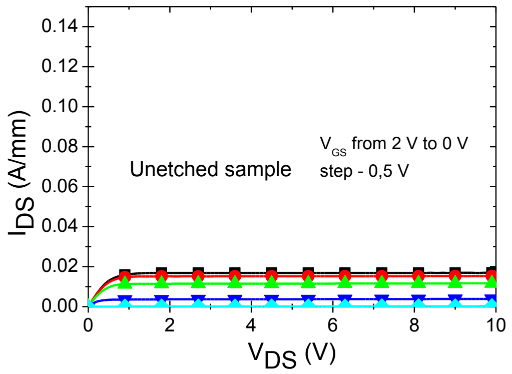

Fig. 2. GaN/InAlN/AlN/GaN HEMT output characteristics before etching the GaN cap.

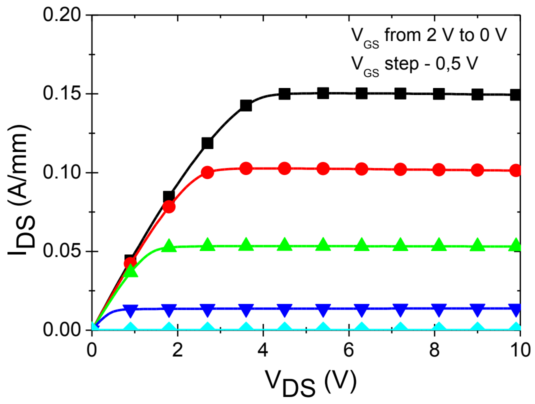

Fig. 3. GaN/InAlN/AlN/GaN HEMT output characteristics after etching the GaN cap, passivating the InAlN surface and annealing.

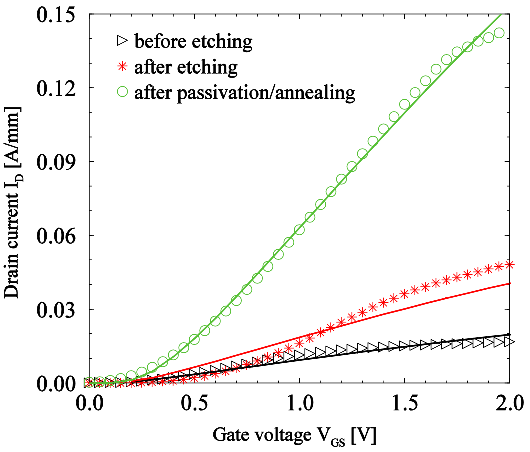

Fig. 4. Experimental (symbols) and calculated (lines) transfer characteristics of HEMTs (at $V_{DS} = 8$ V) before and after etching the GaN cap and after the passivation.

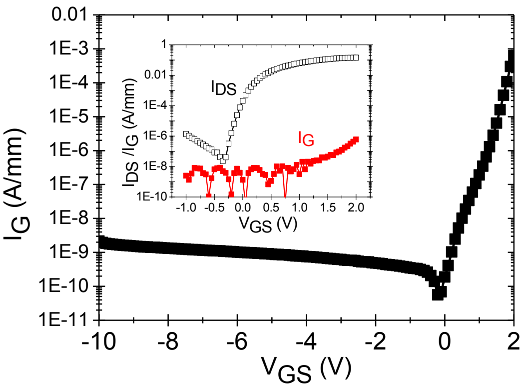

Fig. 5. Two-terminal gate characteristic of passivated and annealed HEMT. Inset shows three-terminal subthreshold characteristics at $V_{DS} = 8$ V.

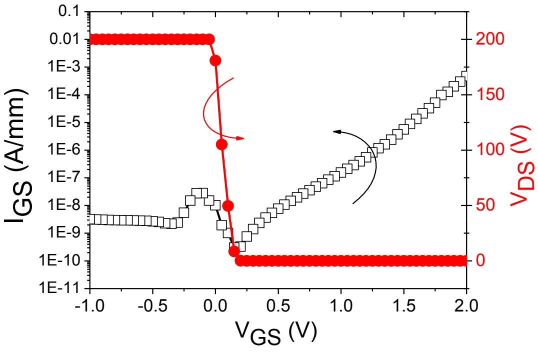

Fig. 6. GaN/InAlN/AlN/GaN HEMT off-state breakdown characteristics determined by a drain injection technique at $I_{DS} = 1$ mA/mm.